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Direct Torque Control of BLDC Motor With Constant Switching Frequency

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***Abstract*— Direct torque control (DTC) has become a popular technique for brushless motor control because it provides fast dynamic torque response. Hysteresis band control is the most popular techniques used in the DTC BLDC motor drive caused the simplest technique. However the conventional DTC have problems as switching frequency that varies with operating conditions and high torque ripple. This paper presents direct torque control (DTC) of BLDC motor with constant switching frequency torque controller. The torque ripple will get reduced by this method constant switching frequency operation. The feasibility of this method in minimizing the torque ripple is verified through some simulation results.**

Keywords—component; Direct torque control (DTC), constant switching frequency, Brushless DC (BLDC).

I. INTRODUCTION

A few years, many researchers studied about direct torque control (DTC) of brushless DC (BLDC) motor. Motor drive evolves from DC drive, Scalar Frequency Control, Flux Vector Control and finally DTC comes into the picture [1]. The improvement most focuses on the system performance, simplicity and reliability. The first vector control was introduced back in 1972 by Hasse, Blaske and Leonhard which named Field Oriented Control (FOC) [2]. The torque and flux of FOC are controlled corresponded to the producing current components (i.e. i_{ds} & i_{qs}) which requires frame transformer, knowledge of machine parameters and current regulated Pulse Width Modulation.

Direct torque control (DTC) was first introduced in Japan by Takahashi and Nagochi on 1986 [3]. DTC is the simple control structure and its offers fast torque and flux control by instantaneous voltage vectors. DTC controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [4]. The different of DTC with FOC are less machines parameter dependence, simpler implementation and quicker dynamic torque response [5]. DTC contains a pair of hysteresis comparators, torque and flux estimators, lookup table for voltage vectors selection and a 3 phase Voltage Source Inverter (VSI). However, there have a few major problems as a variable switching frequency, high torque and flux ripples, varying with speed, load torque and the hysteresis band [6-8], but the most researchers has been focusing to reduce the torque ripple and improving the switching frequency [9-12]. A simple dynamic over modulation method is employed in DTC with constant switching frequency.

Although improvement has been seen in DTC of induction machines, Yong Liu on 2005 [14] and Salih Baris on 2007 [15] introduced DTC method for BLDC motor with DTC method can applied in BLDC motor. The main difference for DTC to be applied for BLDC motor depends on the torque estimation and the representation of the inverter voltage space vector. In this paper considers the application of constant switching frequency with low torque ripple, is presented. Fixed switching frequency torque controller, is used to replace the conventional comparator hysteresis. A fixed switching frequency is obtained by comparing of the triangular waveforms with the error signal compensation using the PI controller. The operations of the new torque controller are similar to the torque controller proposed in [9-13]. The maximum switching capability can be fully utilized because the switching frequency is independent of the operating conditions and equal to the frequency of the triangular waveform. At first, the basic principle DTC of BLDC will be presented in Section II. It is then followed by Section III to discuss DTC with constant switching frequency strategies. Section IV presents the simulation results to compare with conventional DTC of BLDC. Finally, the conclusion is given in Section V.

II. BASIC PRINCIPLE DTC OF BLDC

DTC of brushless DC motor system is chosen as a method of the drive system because it has the potential to further improve the drawback of DTC. The basic concept of DTC is uses two comparator hysteresis (i.e one for torque and one for flux), switching to the voltage vector table selection and a three-phase Voltage Source Inverter (VSI).

System DTC uses a separate control of the stator flux and torque, which is also known as decouple control. The purpose of this control method is to minimize the torque and flux errors to zero by using hysteresis comparator. The hysteresis comparators are not only to determine the proper voltage vector selection, but also the voltage vector selected period. System performance is directly dependent on the estimation of the stator flux and torque. Inaccurate estimates will result in the wrong selection of voltage vector. The basic method for estimating stator flux is by using the stator voltage.

The three phases BLDC motor is operated in a two phase on fashion which means the two phases that produce highest torque are energized based on rotor position while the third phase is off. The three phases VSI for DTC BLDC is represented by six individual solid state semiconductor switches i.e IGBT/MOSFET as shown in Fig. 1 and the output contain six signals (i.e S_1-S_6) which is either 1 or 0. Unlike VSI for DTC induction machine which requires 3 input (S_a, S_b and S_c) gate signal that can be represented by either 1 (upper leg switch is ON) or 0 (lower leg switch is ON).

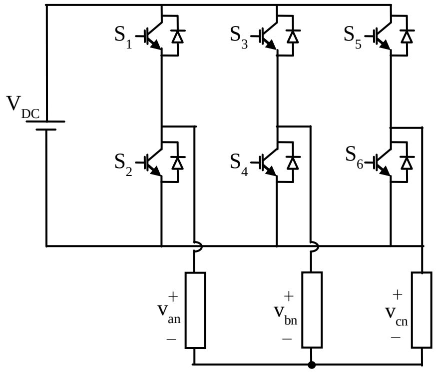


Fig 1. Switching states of the voltage source inverter for DTC of BLDC motor

A simulation model is created using Matlab/Simulink block based on Fig. 2 which show the overall block diagram of the DTC of a BLDC drive system. Torque and flux control is implemented for this drive system. The main differences between the conventional DTC and DTC BLDC are in the voltage vector selection which is using the lookup table from [15] as shown in Table 1, definition of the voltage vector as shown in Fig. 3 and the formula for torque estimation (4). Identification of the six sectors in the α-β plane is based on the Hall Effect signals as shown in Table 2. Flux estimation and current formula which is used is shown below.

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{d\varphi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e} i_{s\beta}\right] \quad (1)$$

$$\frac{d\varphi_{r\alpha}}{d\theta_e} = \frac{e_\alpha}{\omega_e} \; and \; \frac{d\varphi_{r\beta}}{d\theta_e} = \frac{e_\beta}{\omega_e} \quad (2)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e_\beta}{\omega_e} i_{s\beta}\right] \quad (3)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[k_\alpha(\theta_e) i_{s\alpha} + k_\beta(\theta_e) i_{s\beta}\right] \quad (4)$$

$$\varphi_{r\alpha} = \varphi_{rd}\cos\theta_e - \varphi_{rq}\sin\theta_e \quad (5)$$

$$\varphi_{r\beta} = \varphi_{rd}\sin\theta_e + \varphi_{rq}\cos\theta_e \quad (6)$$

$$i_{s\alpha} = i_{sd}\cos\theta_e - i_{sq}\sin\theta_e \quad (7)$$

$$i_{s\beta} = i_{sd}\sin\theta_e + i_{sq}\cos\theta_e \quad (8)$$

$$V_{s\alpha} = \frac{\sqrt{3}}{2} V_{dc}[S_1(S_6 + S_4) - S_2(S_3 + S_5)] \quad (9)$$

$$V_{s\beta} = \frac{\sqrt{3}}{2} V_{dc}[S_6(S_1 + S_3) + S_2(S_3 - S_5) - S_4(S_5 + S_1) - (S_4 \times S_5) + (S_3 + S_6)] \quad (10)$$

TABLE 1. Voltage Vector Selection Table as Proposed in [15].

Torque, τ	Sector, θ					
	1	2	3	4	5	6
1	V_2	V_3	V_4	V_5	V_6	V_1
-1	V_5	V_6	V_1	V_2	V_3	V_4

TABLE 2. Identification of the Six Sectors In The α-β Plane Based On Hall-Effect Signals.

(H_a H_b H_c)	(1 1 0)	(0 1 0)	(0 1 1)	(0 0 1)	(1 0 1)	(1 0 0)
Sector	I	II	III	IV	V	VI

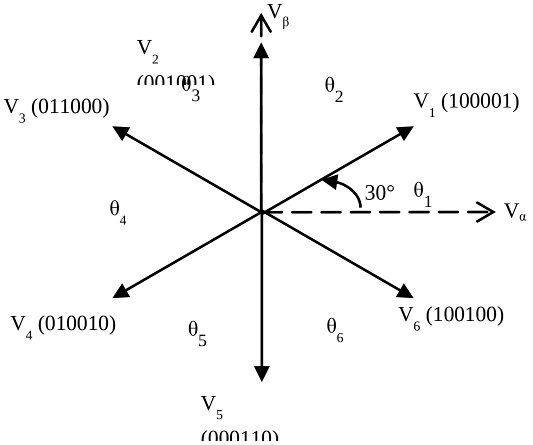


Fig 3. Definition of voltage vector

III. DTC WITH CSF SCHEME (DTC-CSF)

Torque hysteresis controller in DTC is producing the large torque ripple. Therefore, various methods have been proposed to overcome these problems including the use of variable hysteresis bands, predictive control schemes, space vector modulation and intelligent control techniques. In this paper a new torque controller, which produces torque with constant switching frequency and low ripple, has been presented. To provide a constant switching frequency and reduced torque ripple in DTC, the torque hysteresis controller is replaced with a constant frequency torque controller as shown in Fig. 4.

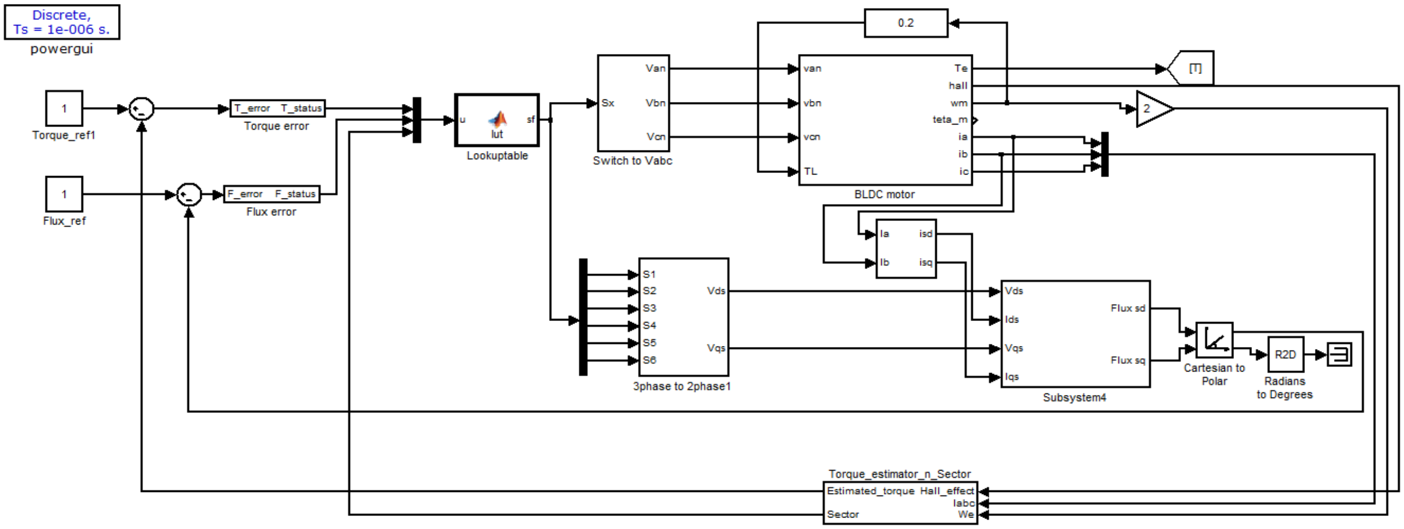


Fig. 2. Block diagram of DTC of BLDC using Matlab/Simulink

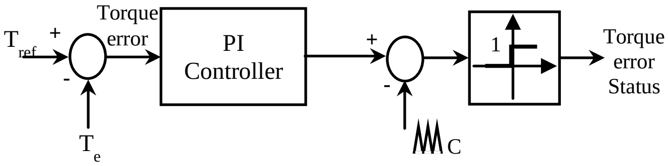


Fig 4. Constant frequency torque controller

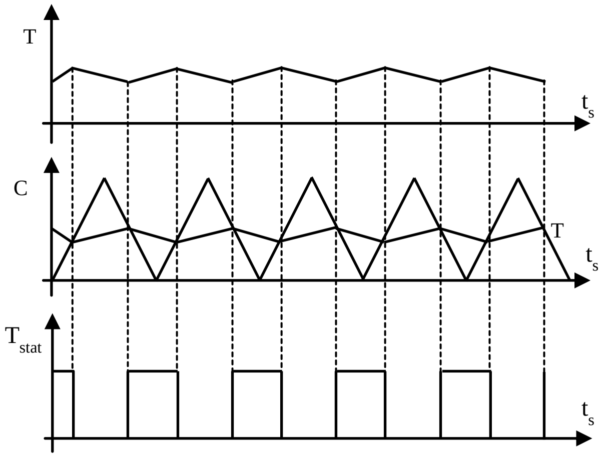


Fig 5. Typical waveform of the constant frequency torque controller.

The constant frequency torque controller (as shown in Fig. 4) consists of one triangular generator, comparators and a proportional integral (PI) controller. A fixed switching frequency is obtained by comparing the triangular waveforms with the compensated error signal. The switching frequency is limited by the sampling period of the processor; however the switching frequency can avoid the switching losses. In principle, the function of the error status T_{stat} torque generated from the constant frequency torque control similar to the hysteresis comparator, which are; 0 or 1. But there is a modification in the lookup table, because in this paper only focused on torque controller while the flux is zero. Figure 5 shows the typical waveforms of the constant frequency torque controller. The torque error status (T_{stat}) generated from the constant frequency torque controller can be described by the following equation.

$$T_{stat} = \begin{Bmatrix} 1 \; for \; T_c \geq C \\ 0 \; for \; T_c \leq C \end{Bmatrix} \tag{11}$$

where T_c is output of Proportional-Integral (PI) control, C is the triangular waveforms, respectively. The triangular waveform is 180^0 out of phase. To establish a constant switching frequency, the frequency and peak-to-peak triangular waveform has been given a fixed value. This is due to set up high triangular waveform frequency to minimize torque ripple. Proportional integral (PI) controller, the gain K_p and K_i values are limited to ensure the absolute slope of the output signal, T_c does not exceed the absolute slope of the triangle waveform. This is to ensure proper operation of the control torque at a constant switching frequency and at the same time to avoid selecting the wrong voltage vector, for a variety of operating conditions.

IV. SIMULATION RESULTS

To study the performance of the DTC of BLDC motor with the modified torque controller and the hysteresis-based controller were performed using the MATLAB/SIMULINK simulation package. The sampling time used for this system is 50µs and the simulation time is 1 sec. The hysteresis band for torque is set at 0.5 N.m and flux reference is set at 0 N.m/Wb. Meanwhile V_{dc} is set at 72 V, torque reference is set at -0.5 N.m and 0.5 N.m. The parameters of the BLDC motor are shown in table 3.

TABLE 3. Control and Motor Parameters Values

Control System	
Torque Hysteresis band	0.5 Nm
Sampling time	1 µs
Frequency	1 kHz
Gain Proportional-Integral (PI) controller	
K_p	2.41
K_i	900
BLDC Motor	

Stator resistance, R_s	11.4 Ω
Stator inductance	43.3 mH
Flux linkage established by magnets	0.19 V.s
Torque constant	1.4 Nm/A
Moment of inertia	0.0422 $Kg.m^2$
Friction factor	0.001 Nms
Pole pairs	4

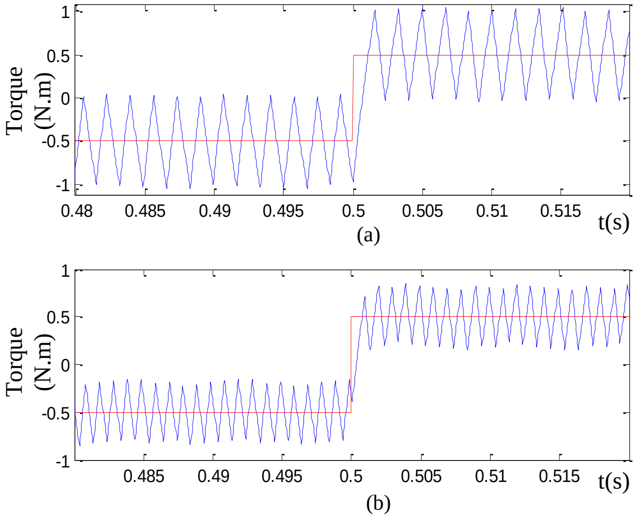
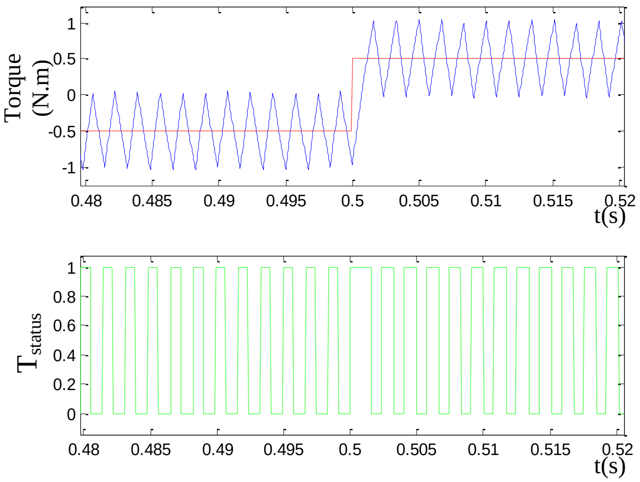


Fig 6. Simulation results of Torque Estimation (a) Hysteresis based (b) Constant switching frequency controller

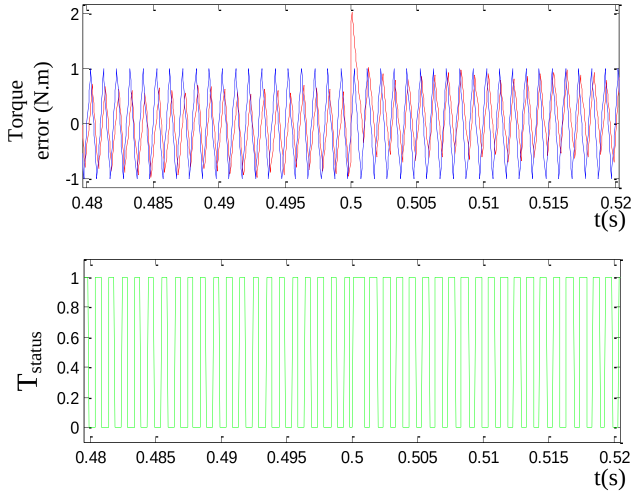
Fig. 6 shows the result of torque (N.m) response for a step input of torque reference for hysteresis controller DTC and constant switching frequency controller DTC. A reference torque which are set at -0.5 N.m during the start up of the simulation and a step change of 0.5 N.m is applied at the simulation time on 1 second. In both method, estimated torque tracks the reference value accurately. From fig. 6 (a) and (b) that in constant switching frequency controller based DTC, the torque ripple is lesser than in hysteresis based DTC. Moreover, it shown the dynamic performance as good as the hysteresis controller based DTC. The torque ripple can be reduced by increasing the frequency of the carrier wave.

Fig. 7 (a) shows the simulation result of the estimated torque with torque reference in the upper trace and torque status in the lower trace for hysteresis controller. Fig. 7(b) shows the tringular carriers with the compensated torque error signal (T_c) in upper trace and torque erroe status in lower trace for the constant switching frequency controller. The modified torque controller have the condition of the torque error, as follows;

$$T_{stat} = \left\{ \begin{matrix} 1\ for\ T_c \geq C \\ 0\ for\ T_c \leq C \end{matrix} \right\} \quad (12)$$



(a) Upper trace- Reference and estimated value of torque, lower trace- Torque error status



(b) Upper trace- Carrier wave and controlled torque error (T_c), lower trace- Torque error status

Fig 7. (a) Hysteresis based (b) Constant switching frequency controller

V. CONCLUSIONS

This paper presents a constant switching frequency torque controller based DTC of brushless DC (BLDC) motor. By using constant switching frequency controller, the switching frequency of the inverter also becomes constant at 1 kHz. As a result, the torque ripple is reduced by replacing the torque hysteresis controller with the constant switching frequency controller. Without sacrificing the dynamic performance of the hysteresis controller, the modified scheme gives constant switching frequency. This work can be implemented using DSP. The work can be extended by increasing the switching frequency above audible range. This is an effective way to shift the PWM harmonics out of human audible frequency range.

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